FAST CONTINUOUS MOVING BED MAGNETIC RESONANCE IMAGING WITH MULTIPLE STATIONARY RECEIVE COILS FOR SENSE RECONSTRUCTION

DESCRIPTION

The present technique relates to the magnetic resonance imaging arts. It finds particular application in conjunction with whole body imaging using the SENSE imaging technique and will be described with particular reference thereto. However, it will be appreciated that the present invention is also applicable to the scanning of other elongated regions and to other techniques using multiple stationary receive coils.

Magnetic resonance scanners have a field of view (FOV) which defines where the region of interest of the subject should be placed to generate a diagnostic image. The magnetic resonance scanner then images a volume of the patient corresponding to the field of view. Typically, when the region of interest is larger than the field of view, one end of the region of interest is positioned in the field of view and a volumetric diagnostic image is generated. The patient is then shifted just under the length of the field of view and another volumetric image is generated. In post-processing, the small region of overlap in the two volumetric images is used to align the two images and to generate a smooth transition between them. The process can then be repeated for subsequent volume images.

One of the drawbacks of stepping the patient to generate a series of volume images is that it is relatively slow and inconvenient for the patient. For example, in magnetic resonance angiography, a contrast agent is injected into the patient's circulatory system. It is advantageous to follow the bolus of contrast agent through the agent's body. The step and image technique is too slow to keep up with the moving bolus and still generate good resolution images.

One solution to this problem is to use the SENSE imaging technique in which multiple data lines are acquired concurrently. See, for example, Maki, et al., Proc. Int'l. Soc. MRM 11:257 (2003) and US Patent No. 6,552,540 to Fuderer. Although faster, this technique generates images which can be viewed as a snapshot taken when the bolus is at one location in the field of view.

It would be advantageous to move the patient continuously through the field of view while conducting imaging. Using coils that acquire a single data line per echo, the continuous patient motion and motion artifacts are negligible for individual data lines and

can be corrected for all data lines.   Following a bolus of contrast agent through a patient requires relatively high speeds (up to 50 mm/s). Although SENSE imaging techniques would image more quickly, the SENSE techniques rely on differences in coil sensitivity to acquire the multiple data lines concurrently. Coil sensitivity is dependent upon the patient and the portion of the patient inside the coil. In order to calibrate the sensitivity of the individual coils used in the SENSE technique for an elongated volume, a series of receive coils could be placed along the full length of the patient or the patient support, calibrated, and moved through the field of view with the patient. This would enable the coils to be precalibrated to the patient portion to which they are adjacent. However, an exceedingly large number of receive coils would be needed over the patient since K≥R coils have to cover the field of view at any time for a SENSE acceleration factor of R. Coil switching and a time consuming calibration would be necessary.

The present application contemplates a new and improved imaging technique which overcomes the above-referenced problems and others.

In accordance with one aspect of the present invention, a magnetic resonance imaging apparatus defines a fixed field of view (FOV) in which magnetic resonance is excited and phase and frequency encoded. A plurality of fixed global receive coils acquire resonance signals from the fixed field of view. A means is provided for moving a subject continuously through the fixed field of view during excitation, phase and frequency encoding of the magnetic resonance, and the acquisition of the magnetic resonance signals. In this manner, each of the fixed global receive coils receives resonance signals in parallel from the subject over an elongated virtual field of view (vFOV) which is longer than the fixed field of view. A means generates coil sensitivity patterns corresponding to the fixed field of view for the global receive coils. Another means maps the sensitivity patterns from the fixed field of view to the virtual field of view.

In accordance with another aspect of the present invention, a magnetic resonance imaging method is provided. Data is acquired with a plurality of global receive coils which are fixed with respect to a field of view through which a subject can move continuously. In this manner, the magnetic resonance signals can be acquired over a virtual field of view defined by an elongated region of the subject which is moved through

the fixed field of view. Sensitivity patterns corresponding to the fixed field of view are generated for the global receive coils. The sensitivity patterns are mapped from the fixed field of view to the virtual field of view.

One advantage of the present invention is that it quickly generates a good quality image of an elongated area.

Another advantage of the present invention resides in whole-body magnetic resonance imaging.

An advantage in magnetic resonance angiography applications is that the patient can be moved longitudinally through the field of view at a speed which is substantially the same as a contrast agent bolus moves along the patient's circulatory system.

Another advantage resides in the adaptation of the SENSE imaging technique to continuously moving subjects.

Still further advantages and benefits of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The FIGURES are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 is a diagrammatic illustration of a magnetic resonance imaging system in accordance with the present invention;

FIGURE 2A illustrates a linear phase-encoding trajectory versus time;

FIGURE 2B illustrates a composition of a virtual field of view sensitivity map for an exemplary one of the receive coils with the linear acquisition order of FIGURE 2A;

FIGURE 3A illustrates a subsequent high and low spatial frequency scanning order;

FIGURE 3B illustrates the composition of the virtual field of view sensitivity map for one of the receive coils using the acquisition order of FIGURE 3A.

With reference to FIGURE 1, a magnetic resonance imaging system **10** includes a main magnet assembly **12** which generates a temporally constant magnetic field B_0 longitudinally through an examination region **14**. Gradient magnetic field coils **16** driven by gradient amplifiers **18** generate magnetic field gradients across the examination region, preferably in three orthogonal directions. A stationary whole-body RF resonance excitation coil assembly **20** with a radio frequency transmitter **22** excites and manipulates magnetic resonance of selected dipoles within the examination region **14**. A plurality of fixed global receive coils **24a**, **24b**, and **24c** is each associated with an RF receiver **26a**, **26b**, **26c** for receiving resonance signals from the examination region **14**. Although three global receive coils are illustrated for simplicity of illustration, it is to be appreciated that a larger number of receive coils and associated receivers are contemplated.

The gradient and RF coils define a field of view (FOV) centrally in the examination region within which resonance is excited and from which useable magnetic resonance signals are received for imaging.

A subject support **28** is driven by a motor **30** or other means for moving the subject support continuously through the field of view. By imaging continuously as the subject moves through the examination region, data is acquired over a virtual field of view (vFOV) corresponding to the length of the subject which is translated through the field of view. In the preferred whole-body imaging embodiment, the virtual field of view has the same transverse cross-section as the field of view, but extends the length of the subject's body.

As the motor **30** moves the subject support **28** and the subject continuously through the examination region **14**, a sequence controller **32** controls the gradient amplifiers **18** and the RF transmitter **22** to conduct an imaging sequence in which data is phase and frequency encoded along selected trajectories relative to the field of view in k-space. The scanner is preferably operated in a fast field echo sequence.

In a three-dimensional preparatory measurement, the complex coil sensitivity patterns in the stationary B_0 field of the fixed field of view are monitored precisely. This is done for a static table position using the widest region of the patient, such as the shoulders, for the widest covering of the field of view. More specifically, the

central k-space data from the three-dimensional preparatory measurement is temporarily stored in a data buffer or memory 34. A position monitor or encoder 36 determines the position of the subject support 28 to correlate the fixed field of view (FOV) of the preparatory measurement with the virtual field of view (vFOV).

A reconstruction processor 40 includes a normalizing image or sensitivity pattern reconstruction processor or means 42 which reconstructs the data from the preparatory measurement into a sensitivity pattern or normalizing image which is stored in a sensitivity pattern or normalizing image memory 44. Preferably, in another reference position, such as the abdomen, the preparatory measurement is repeated and the additional sensitivity patterns is generated and stored in the sensitivity pattern memory. A fixed field of view to virtual field of view mapping processor or means 46 maps the sensitivity patterns from the frame of reference of the fixed field of view (FOV), in which it was collected, across the virtual field of view (vFOV). . The sensitivity plot is stored in a virtual field of view (vFOV) sensitivity patterns memory 48 and is used to unfold image data of the virtual field of view in a SENSE unfolding procedure as explained below.

However, because the sensitivity map of the receive coils 26a-26c varies with patient loading and because patients are typically not homogeneous along their entire length, a plurality of sensitivity patterns are preferably generated along the patient length. These additional sensitivity patterns can be generated in preliminary measurements with different selected portions of the subject in the fixed field of view, or can be generated by measurements interleaved during the imaging sequence. For example, adjacent each or selected zero crossings of k-space, a complete rather than undersampled set of central k-space data lines can be generated for the sensitivity pattern reconstruction processor 42 to use to update the sensitivity patterns.

With reference to FIGURE 2A, in a preferred embodiment, image data is generated along linear trajectories through k-space starting at a maximum negative phase encoding and steps progressively with time through the zero phase encode point to the maximum positive phase encoding. The continuous subject motion or z-direction is chosen parallel to the frequency encoding direction (readout) of the magnetic resonance sequence. The phase encoding is performed in a perpendicular direction (x, y). The sequence is then repeated, all of the time the subject moving continuously through the field of view. The plurality of global receive coils 26a, 26b, 26c read out an undersampled

plurality of data lines of k-space concurrently in the field of view frame of reference. The data lines for each receive coil are optionally stored or buffered in corresponding portions of the field of view frame of reference memory or buffer **34** along with subject support position in formation which translates the image data into the virtual field of view (vFOV) from the fixed field of view (FOV).

The data from each of the global receive coils is forwarded to a folded image data reconstruction processor or means **50** of the reconstruction processor **40** which reconstructs the undersampled data from each global receive coil into folded images which are stored in a folded image memory or buffer **52**. An SENSE unfolding processor or means **54** combines and unfolds the folded images using the sensitivity pattern mapped to the virtual field of view from the vFOV sensitivity pattern memory **44** to form a single whole-body image corresponding to the entire virtual field of view. The whole-body image is stored in a whole-body or virtual field of view image memory **60**. A video processor **62** withdraws selected portions of the whole body image and formats the image data into appropriate form for display on a monitor **64**.

With reference to FIGURE 2B, although the relationship between the continuously traveling virtual field of view (vFOV) and the fixed field of view (FOV) is a complex relationship, the coil sensitivity patterns are smooth functions of space. The mapping means **46** maps the coil sensitivity pattern of each coil to areas inside the virtual field of view corresponding to the image data at the point of time when the k=0 acquisitions are to be collected to the virtual field of view. The sensitivity in k-space concentrates on low, central spatial frequencies. FIGURE 2B illustrates a composition of the virtual field of view sensitivity map **46** for one of the receive coils acquiring data using the linear acquisition order of FIGURE 2A, in which the scanning sequence passes periodically through k=0. In the illustrated linear case, the sensitivity pattern corresponding to the k=0 measurement is used for all data lines within the corresponding linear sweep through k-space. When high spatial frequencies are acquired toward the edges of k-space, the longitudinal translation of the patient causes the sensitivity pattern to be displaced from the assumed area within the virtual field of view. Although in principle, this could lead to high frequency ghosting in the SENSE reconstruction, under practical conditions it has been found that the effect is negligible and can be ignored. Variations of the coil sensitivity pattern in the direction of motion are smooth functions.

In an exemplary embodiment in which the subject is moving at 40 millimeters/second through a 20-35 centimeter field of view, and a voxel size of 1 millimeter and a readout of 4 milliseconds, the motion during one data line acquisition is significantly less than a voxel . Thus motion artifacts in the data line readout are negligible. A typical virtual field of view extends 2.0 meters.

In a more specific embodiment, the fixed field of view is 25 centimeters and the virtual field of view is 2.0 meters. In a preliminary setup mode, at least low frequency data lines are generated for eight 25 centimeter fixed fields of view which end-to-end, span the virtual field of view. The low frequency data for each of the six fixed fields of view is reconstructed into sensitivity patterns, which sensitivity patterns are mapped from the fixed field of view to the virtual field of view. Then, during the continuous motion and data acquisition, the patient is moved at a speed relative to the data acquisition speed such that the patient moves 25 centimeters in the time that it takes to collect the data along one repetition of the k-space trajectory. The image data collected along the k-space trajectory is reconstructed into folded images which are unfolded using the sensitivity pattern in the vFOV.

Rather than sampling k-space linearly as illustrated in FIGURE 1, other k-space sampling patterns are also contemplated. For example, as illustrated in FIGURE 3A, k-space is sampled starting at zero and working alternately to the opposite high frequency portions of k-space. The alternate high and low spatial frequency scanning leads to a more complicated mapping between the field of view and the virtual field of view as illustrated in FIGURE 3B with a double periodicity. Other mappings of k-space, such as spiral, radial, and the like as are known in the art are also contemplated.

The invention has been described with reference to the preferred embodiments. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.